Alignment of the spins of supermassive black holes prior to merger

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ABSTRACT

Recent numerical relativistic simulations of black hole mergers suggest that in certain alignments the emission of gravitational radiation can produce a kick of several thousand kilometers per second. This exceeds galactic escape speeds, hence unless there a mechanism to prevent this, one would expect many galaxies that had merged to be without a central black hole. Here we show that in most galactic mergers, torques from accreting gas suffice to align the orbit and spins of both black holes with the large-scale gas flow. Such a configuration has a maximum kick speed < 200 km s^{-1}, safely below galactic escape speeds. We predict, however, that in mergers of galaxies without much gas, the remnant will be kicked out several percent of the time. We also discuss other predictions of our scenario, including implications for jet alignment angles and X-type radio sources.

Subject headings: black hole physics – galaxies: nuclei – gravitational waves — relativity

1. Introduction

When two black holes spiral together and merge, they emit gravitational radiation which in general possesses net linear momentum. This accelerates (i.e., "kicks") the merger remnant relative to the initial binary center of mass. Analytical calculations have determined the accumulated kick speed from large separations until when the holes plunge towards each other (Peres 1962; Bekenstein 1973; Fitchett 1983; Fitchett & Detweiler 1984; Redmount & Rees 1989; Wiseman 1992; Favata, Hughes, & Holz 2004; Blanchet, Qusailah, & Will 2005; Damour & Gopakum 2006), but because the majority of the kick is produced between plunge and merger, fully general relativistic numerical simulations are necessary to determine the full recoil speed.

Fortunately, the last two years have seen rapid developments in numerical relativity. Kick speeds have been reported for non-spinning black holes with different mass ratios (Herrmann, Shoemaker, & Laguna 2006; Baker et al. 2006; Gonzalez et al. 2006) and for binaries with spin axes parallel or antiparallel to the orbital axes (Herrmann et al. 2007; Koppitz et al. 2007; Baker et al. 2007), as well as initial explorations of more general spin orientations (Gonzalez et al. 2007; Campanelli et al. 2007a,b). For mergers with low spin or spins both aligned with the orbital angular momentum, these results indicate maximum kick speeds < 200 km s^{-1}. Remarkably, however, it has recently been shown that when the spin axes are oppositely directed and in the orbital plane, and the spin magnitudes are high (dimensionless angular momentum $\hat{a} \equiv cJ/GM^2 \sim 1$), the net kick speed can perhaps be as large as ~ 4000 km s^{-1} (Gonzalez et al. 2007; Schnittman & Buonanno 2007; Campanelli et al. 2007b).

The difficulty this poses is that the escape speed from most galaxies is < 1000 km s^{-1} (see Figure 2 of Merritt et al. 2004), and the escape speed from the central bulge is even smaller. Therefore, if large recoil speeds are typical, one might expect that many galaxies that have undergone major mergers would be without a black hole. This is in clear contradiction to the observation that galaxies with bulges all appear to have central supermassive black holes (see Ferrarese & Ford 2005). It therefore seems that there is astrophysical avoidance of the types of supermassive black hole mergers that would lead to kicks beyond galactic escape speeds. From the numerical relativity results, this could happen if (1) the spins are all small, (2) the mass ratios between merging black holes are all much less than unity, or (3) the spins tend to align with each other and the orbital angular momentum.

The low-spin solution is not favored observationally. X-ray observations of several active galactic nuclei reveal relativistically broadened Fe Kα fluorescence lines indicative of spins $\hat{a} > 0.9$ (Iwasawa et al. 1996; Fabian et al. 2002; Reynolds & Nowak 2003; Brenneman & Reynolds 2006). A similarly broad line is seen in the stacked spectra of active galactic nuclei in a long exposure of the Lockman Hole (Streblyanska et al. 2005). More generally, comparison of the integrated light from AGN (after corrections for obscuration) with the mass density of supermassive black holes (Sołtan 1982; Yu & Tremaine 2002) implies an average radiation efficiency $L/\dot{M}c^2 \sim 0.2$, which corresponds to $\hat{a} \sim 0.95$ if this is the binding energy at the innermost stable circular orbit.

Mass ratios much less than unity may occur in some mergers, and if the masses are different enough then the kick speed can be small. For example, the functional form proposed by Campanelli et al. (2007b) suggests that if the spin parameters are $\hat{a}_1 = -\hat{a}_2 = 1$ and the mass ratio is $q \equiv m_1/m_2 \leq 1$, then the maximum kick speed is proportional to $q^2/(1+q)^4$. For $q < 0.1$ this scales roughly as q^2 and hence kicks are small. However, for $q > 0.2$ the maximum kick is within a factor ~ 3 of the kick possible for $q = 1$. An unlikely conspiracy would thus seem to be required for the masses always to be different by the required factor of several. Some tens of percent of galaxies appear to have undergone at least one merger with mass ratio $> 1/4$ within redshift $z < 1$ (for recent observational results with different methods, see Bell et al. 2006b; Lotz et al. 2006, and for a recent simulation see Maller et al. 2006). The well-established tight correlations between central black hole mass and galactic properties such as bulge velocity dispersion (see Ferrarese & Ford 2005 for a review) then suggest strongly that mergers of comparable-mass black holes should be common.

The most likely solution therefore seems to be that astrophysical processes tend to align the spins of supermassive black holes with the orbital axis. This astrophysical alignment is the subject of this *Letter*. We distinguish alignment in two types of mergers. In a "dry" merger, gas is unimportant and hence the binary is essentially isolated and the spins only precess and evolve under the influence of spin-orbit coupling and gravitational radiation dissipation. In a "wet" merger, gas accretion and torques are dynamically important.

Here we show that wet mergers tend to lead to strong alignment of the spin axes with the orbital angular momentum and thus to kick speeds much less than the escape speeds of sizeable galaxies. In contrast, dry mergers show no net tendency for alignment, assuming an initially uniform distribution of spin and orbital angular momentum vectors. We demonstrate this aspect of dry mergers in § 2. In § 3 we discuss wet mergers, and show that observations and simulations of nuclear gas in galactic mergers suggest that the black holes will be aligned efficiently. We discuss consequences and predictions of this alignment in § 4.

2. Dry mergers

Several recent models and observations have been proposed as evidence that some galactic mergers occur without a significant influence of gas. Possible signatures include the metal richness of giant ellipticals (e.g., Naab & Ostriker 2007) and slow rotation and the presence of boxy orbits in the centers of some elliptical galaxies (e.g., Bell et al. 2006a; Naab, Jesseit, & Burkert 2006).

Consider such a gas-free merger, and assume that we can therefore treat the gradual inspiral of two spinning black holes as an isolated system. As laid out clearly by Schnittman (2004), throughout almost the entire inspiral there is a strong hierarchy of time scales, such that $t_{\rm inspiral} \gg t_{\rm precess} \gg t_{\rm orbit}$. Schnittman (2004) therefore derived orbit-averaged equations for the spin evolution in the presence of adiabatic dissipation. Such effects can lead to relaxation onto favored orientations. Indeed, Schnittman (2004) finds that if the more massive black hole's spin is initially oriented nearly parallel to the orbital angular momentum vector, then the two spins wind up nearly parallel to each other although not necessarily along the orbital axis. However, he also finds that if the spin of the more massive hole is initially close to antiparallel to the orbital axis, then there is no special spin-spin alignment. The question is then whether, with the uniform distribution of orbital and spin directions that seems expected in galactic mergers, there is a tendency to align in such a way that the net kicks are small.

As Figure 1 shows, there is no such tendency. Using equations A8 and A10 from Schnittman (2004), we have evolved the angles between the two spin vectors, and between the spins and the orbital angular momentum. We assume a mass ratio of 0.55 : 0.45, spin parameters $\hat{a}_1 = \hat{a}_2 = 1.0$, and an initially isotropic distribution of angles, and evolve the binary from a separation $1000m$ (where $m = 1$ is the total mass of the binary) to a separation $10m$. Figure 1 shows the dot product with the orbital angular momentum of the final spin of the more massive black hole ($\cos\theta_{1,fi}$), and of the final spin of the less massive black hole ($\cos\theta_{2,fi}$), at $10m$. Overall, there is no correlation between these angles, and also no tendency to align the two spins with each other. Thus, although (as we confirm) Schnittman (2004) showed that for special orientations the spins might align (e.g., for an initial $\cos\theta_1 \approx 1$, or as we also discovered, for an initial $\cos\theta_2 \approx -1$), the initial conditions resulting in such alignment are special and subtend only a small solid angle. For isotropically distributed initial spins and orbits, the spins and orbits at close separation are also close to isotropically distributed.

The conclusion is that dry mergers alone cannot align spins sufficiently to avoid large kicks due to gravitational radiation recoil. Indeed, Schnittman & Buonanno (2007) find that for mass ratios $q > 0.25$ and isotropic spin directions, $\sim 8\%$ of mergers result in kick speeds > 1000 km s^{-1} and $\sim 30\%$ yield speeds > 500 km s^{-1}. The high maximum speeds inferred by Campanelli et al. (2007b) might increase these numbers. We now discuss wet mergers, which can naturally reduce the kick speeds by aligning black hole spins with their orbital axis.

3. Wet Mergers

Consider now a gas rich environment, which is common in many galactic mergers. The key new element is that gas accretion can exert torques that change the direction but not the magnitude of the spin of a black hole, and that the lever arm for these torques can be tens of thousands of gravitational radii (Bardeen & Petterson 1975; Natarajan & Pringle 1998; Natarajan & Armitage 1999). In particular, Natarajan & Pringle (1998) and Natarajan & Armitage (1999) demonstrate that the black hole can align with the larger scale accretion disk on a timescale that is as short as 1% of the accretion time. An important ingredient of this scenario is the realization by Papaloizou & Pringle (1983) that the warps are transmitted through the disk on a timescale that is shorter by a factor of $1/2\alpha^2$ compared with the transport of the orbital angular momentum in flat disks. The question that distinguishes wet from dry mergers is therefore whether the accreted mass is $\geq 0.01 - 0.1 M_{\rm bh}$ during the sinking of the black holes towards the center of the merged galaxy, where $M_{\rm bh}$ is a black hole mass.

Numerical simulations show that galactic mergers trigger large gas inflows into the central kiloparsec (Barnes & Hernquist 1991, 1996; Mihos & Hernquist 1994; Di Matteo, Springel, & Hernquist 2005; Kazantzidis et al. 2005). The effect is especially dramatic for mergers of gas rich galaxies, which can result in a $\sim 10^9\,{\rm M}_\odot$ central gas remnant with a diameter of only 200 pc (Barnes & Hernquist 1991). Such mergers are thought to be the progenitors of ultraluminous infrared galaxies. Gas inflows are also found in simulations of mergers between disk galaxies and intermediate-mass satellites (Mihos & Hernquist 1994). Kazantzidis et al. (2005) find that the strong gas inflows observed in cooling and star formation simulations always produce a rotationally supported nuclear disk of size $\sim 1 - 2$ kpc with peak rotational velocities in the range of 250−300 ${\rm km\,s^{-1}}$.

The results of numerical simulations are in good agreement with observations, which also show that the total mass of the gas accumulated in the central region of merger galaxies can reach $10^9 - 10^{10}\,{\rm M}_\odot$ and in some cases account for about a half of the enclosed dynamical mass (Tacconi et al. 1999, see our Table 1). Observations of the nearby mergers Arp 220 and NGC 6240 imply that the cold, molecular gas settles into a geometrically thick, rotating structure with velocity gradients similar to these obtained in simulations and with densities in the range $10^2 - 10^5\,{\rm cm^{-3}}$ (Scoville, Yun, & Bryant 1997; Sakamoto et al. 1999; Tacconi et al. 1999; Armus et al. 2006). The projected separation of the inferred nuclei in Arp 220 is about 330 pc (Graham et al. 1990) and for the active nuclei of NGC 6240 is ~ 1 kpc (Komossa et al. 2003b). Both observations and simulations of multiphase interstellar matter with stellar feedback show a broad range of gas temperatures, where the largest fraction of gas by mass has a temperature of about 100 K (Wada & Norman 2001, 2002). These physical properties of the gas disks are also well matched by the models of radiation pressure-supported starburst disks (Thompson, Quataert, & Murray 2005), the predictions of which are also shown in Table 1.

We therefore consider an idealized model based on these observations and simulations. In our model, the two black holes are displaced from the center embedded within the galactic-scale gas disk. We are mainly concerned with the phase in which the holes are separated by hundreds of parsecs, hence the enclosed gas and stellar mass greatly exceeds the black hole masses and we can assume that the black holes interact independently with the disk. Based on the results of Escala et al. (2004, 2005), Mayer et al. (2006), and Dotti, Colpi, & Haardt

(2006) the time for the black holes to sink from these separations to the center of the disk due to dynamical friction against the gaseous and stellar background is $\leq 5 \times 10^7$yr, which is comparable to the starburst timescale, $\sim 10^8$yr (Larson 1987).

The accretion rate onto the holes then depends on local capture dynamics as well as the large-scale velocity flow in the disk. Locally, one can estimate the Bondi radius $R_{\rm Bondi} = GM_{\rm bh}/v_g^2 \approx 40\ {\rm pc}\,(M_{\rm bh}/10^8\ M_\odot)(v_g/100\ {\rm km\ s^{-1}})^{-2}$ that would be appropriate for a total gas speed at infinity, relative to a black hole, of v_g (we use a relatively large scaling of 100 km s^{-1} for this quantity to be conservative and to include random motions of gas clouds as well as the small thermal speed within each cloud). However, if the Bondi radius is larger than the Hill radius $R_{\rm Hill} = r\,(M_{\rm bh}/3M_{\rm enclosed})^{1/3}$, where $M_{\rm enclosed}$ is the mass of the enclosed gas and stars and r is the distance from the galactic center, then the large-scale potential dominates over the black hole potential and gas outside this region cannot be captured. The accretion rate is therefore the minimum of the Bondi rate

$$\dot{M}_{\rm Bondi} \approx 1\ M_\odot\,{\rm yr}^{-1} \left(\frac{v_g}{100\,{\rm km\,s^{-1}}}\right)^{-3} \left(\frac{n}{100\,{\rm cm^{-3}}}\right) \left(\frac{M_{\rm bh}}{10^8\ {\rm M_\odot}}\right)^2 \tag{1}$$

and the rate at which mass flows through the Hill sphere (see Goodman & Tan 2004)

$$\begin{aligned} \dot{M}_{\rm Hill} &\sim \Sigma\Omega R_{\rm Hill}^2 \\ &\approx 1\ M_\odot\,{\rm yr}^{-1}\, f_H^2 \left(\frac{h}{50\,{\rm pc}}\right) \left(\frac{r}{500\,{\rm pc}}\right) \left(\frac{n}{100\,{\rm cm^{-3}}}\right) \left(\frac{v_{\rm orb}}{200\ {\rm km\ s^{-1}}}\right) \left(\frac{M_{\rm bh}/10^8\,M_\odot}{M_{\rm enclosed}/10^9\,M_\odot}\right)^{2/3} \end{aligned} \tag{2}$$

Here $f_H = 3-4$ is a numerical factor from Goodman & Tan (2004), h is the half-thickness of the disk, n is the number density, and $\Omega = v_{\rm orb}/r$ is the angular velocity of gas around the galactic center.

At either of these rates, the holes will acquire 1-10% of their mass in a time short compared to the time needed for the holes to spiral in towards the center or the time for a starburst to deplete the supply of gas. We note that the accreted gas has significant angular momentum relative to the black holes: analogous simulations in a planetary formation environment suggest that the circularization radius is some hundredths of the capture radius (e.g., Hamilton & Burns 1991, 1992). This corresponds to more than 10^5 gravitational radii, hence alignment of the black hole spin axes is efficient. We also note that although gap formation can decrease the accretion rates significantly, formation of a gap requires clearing of an annulus with a width equal to the Hill sphere (e.g., Goodman & Tan 2004). Therefore, if a gap has formed then enough mass has already accreted to align the holes.

If the black hole spins have not been aligned by the time their Bondi radii overlap and a hole is produced in the disk, further alignment seems unlikely. The reason is twofold: the shrinking of the binary due to circumbinary torques is likely to occur within $< \text{few} \times 10^7$ yr (Escala et al. 2004, 2005), and accretion across the gap only occurs at $\sim 10\%$ of the rate it would have for a single black hole (Lubow, Seibert, & Artymowicz 1999; Lubow & D'Angelo 2006; MacFadyen & Milosavljevic 2006), with possibly even smaller rates onto the holes themselves. This therefore leads to the dry merger scenario, suggesting that massive ellipticals or ellipticals with slow rotation or boxy orbits have a several percent chance of having ejected their merged black holes but that other galaxy types will retain their holes securely.

4. Predictions, Discussion and Conclusions

We propose that when two black hole accrete at least $\sim 1 - 10\%$ of their masses during a gas rich galactic merger, their spins will align with the orbital axis and hence the ultimate gravitational radiation recoil will be < 200 km s^{-1}. In this section we discuss several other observational predictions that follow from this scenario.

The best diagnostic of black hole spin orientation is obtained by examining radio galaxies. All viable jet formation mechanisms result in a jet that is initially launched along the spin axis of the black hole. This is the case even if the jet is energized by the accretion disk rather than the black hole spin since the orientation of the inner accretion disk will be slaved to the black hole spin axis by the Bardeen-Petterson effect (Bardeen & Petterson 1975).

A basic prediction of our work is that in gas-rich mergers black holes will be well aligned prior to the final merger event and, therefore, one will never witness dramatic spin orientation changes during the final merger. Active galaxies are powered by gas accretion, hence we expect that if radio galaxies are the product of mergers, no sharp change in jet direction will be seen. However, there is a class of radio-loud AGN known as "X-shaped radio galaxies", that possess morphologies interpreted precisely as a rapid ($< 10^5$ yr) re-alignment of black hole spin during the final stages of a binary black hole merger (Ekers et al. 1978; Dennett-Thorpe et al. 2002; Wang, Zhou & Dong 2003; Komossa 2003a; Lal & Rao 2007; Cheung 2007). These sources have relatively normal "active" radio lobes (often displaying jets and hot-spots) but, in addition, have distinct "wings" at a different position angle. The spin realignment hypothesis argues that the wings are old radio lobes associated with jets from the one of the pre-merger black holes in which the spin axis possessed an entirely different orientation to the post-merger remnant black hole (Merritt & Ekers 2002). If this hypothesis is confirmed by, for example, catching one of these systems in the small window of time in which both sets of radio lobes have active hot spots, it would contradict our scenario unless it can be demonstrated that all such X-shaped radio-galaxies originate from dry mergers.

However, the existence of a viable alternative mechanism currently prevents a compelling case from being made that X-shaped radio sources are a unique signature of mis-aligned black hole mergers. The collision and subsequent lateral expansion of the radio galaxy backflows can equally well produce the observed wings (Capetti et al. 2002). Indeed, there is circumstantial evidence supporting the backflow hypothesis. Kraft et al. (2005) present a Chandra observation of the X-shaped radio galaxy 3C 403 and find that the hot ISM of the host galaxy is strongly elliptical, with a (projected) eccentricity of $e \sim 0.6$. Furthermore, the wings of the "X" are closely aligned with the minor axis of the gas distribution, supporting a model in which the wings correspond to a colliding backflow that has "blown" out of the ISM along the direction of least resistance. Although 3C 403 is the only X-shaped radio galaxy for which high-resolution X-ray maps of the hot ISM are available, Capetti et al. (2002) have noted that a number of X-shaped sources have wings that are oriented along the minor axis of the *optical* host galaxy. This suggests that the conclusion of Kraft et al. (2005) for 3C 403 may be more generally true.

There is one particular system, 0402+379, that might provide a particularly direct view of spin alignment in a binary black hole system. Very Long Baseline Array (VLBA) imaging of this radio galaxy by Maness et al. (2004) discovered two compact flat spectrum radio cores, and follow-up VLBA observations presented by Rodriguez et al. (2006) showed the cores to be stationary. A binary supermassive black hole is the most satisfactory explanation for this source, with the projected distance between the two black holes being only 7.3 pc. Within the context of our wet-merger scenario, these two black holes already have aligned spins. Existing VLBA data only show a jet associated with one of the radio cores. We predict that, if a jet is eventually found associated with the other radio core, it will have the same position angle as the existing jet.

Another basic prediction of our model is that the spin of the immediate pre-merger black holes as well as the final remnant black hole will be aligned with the angular momentum vector of the large scale gas disk associated with the galactic merger. Evidence for this already exists. Perlman et al. (2001) imaged the host galaxies of three compact symmetric objects and discovered nuclear gas disks approximately normal to the jet axis. The presence of such a nuclear gas disk as well as disturbances in the outer isophotes of all three host galaxies suggests that these galaxies had indeed suffered major wet mergers within the past 10^8 yr.

In conclusion, we propose that in the majority of galactic mergers, torques from gas accretion align the spins of supermassive black holes and their orbital axis with large-scale gas disks. This scenario helps explain the ubiquity of black holes in galaxies despite the potentially large kicks from gravitational radiation recoil. Further observations, particularly of galaxy mergers that do not involve significant amounts of gas, will test our predictions and may point to a class of large galaxies without central black holes.

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Table 1. Properties of gas disks

Source	M_{disk} ($M_{\odot}$)	$2R_{disk}$ (kpc)	$2h$ (pc)	n (cm^{-3})	T (K)	Rotation
NGC 6240 [a]	2×10^9	~ 0.5	...	$\sim 10^2$	~ 100	Indicated
Arp 220 [b]	$\sim 10^{10}$	~ 1	$30-80^c$	$\geq 10^4 - 10^5$	≥ 40	Yes
Simulations [d]	$10^8 - 10^9$	~ 2	$20-100$	$10^3 - 10^4$	$10^2 - 10^4$	Yes
Models [e]	$\sim 10^9$	2	~ 70	$\sim 10^2$	50-100	By construction

[a]Tacconi et al. (1999); Armus et al. (2006). Here, $2R_{disk}$ represents the projected disk size.

[b]Scoville et al. (1997); Sakamoto et al. (1999); Eckart & Downes (2001). Here, $2R_{disk}$ represents the projected disk size.

[c]Smaller value derived from the mass, density, and size of the disk (Sakamoto et al. 1999). Larger value derived from assumption that velocity dispersion is due to turbulent motions (Eckart & Downes 2001).

[d]Kazantzidis et al. (2005); Dotti et al. (2006); Mayer et al. (2006); Wada & Norman (2001, 2002).

[e]Thompson et al. (2005). The values calculated from the radiation pressure-supported disk model for assumed gas fraction of 0.1, disk radius of 1kpc, stellar velocity dispersion of 200 $\mathrm{km\,s^{-1}}$, and Toomre $Q \sim 1$

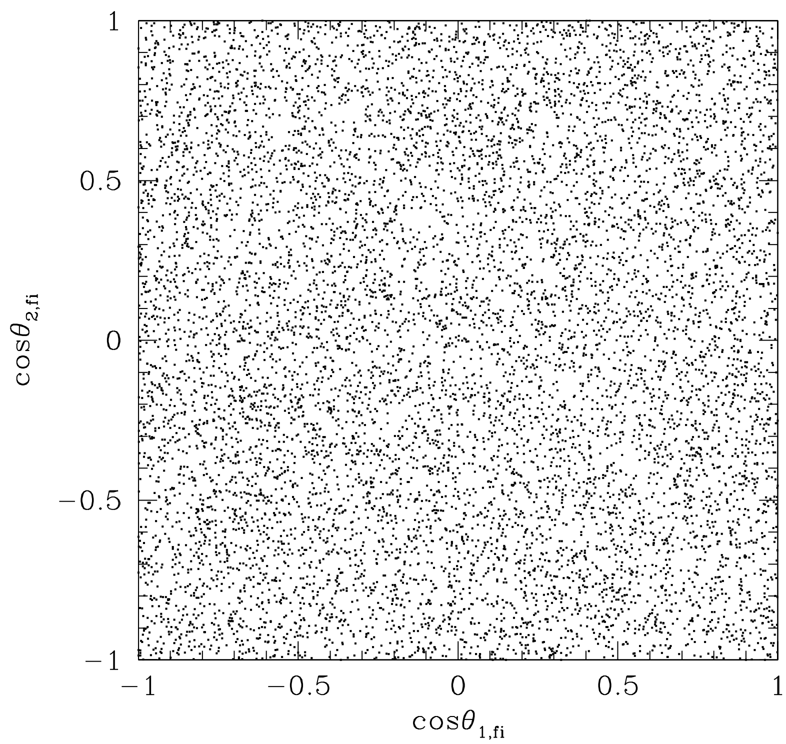

Fig. 1.— Demonstration that in dry mergers there is no tendency to align black hole spin angles. Here we show the distribution of the dot products with the orbital angular momentum axis of the final spin axis of the larger mass ($\cos\theta_{1,fi}$) and smaller mass ($\cos\theta_{2,fi}$) black hole, evolved using the formalism of Schnittman (2004). We assume that at an initial separation of $1000m$ (where $m = 1$ is the total mass of the binary) the spin directions and orbital axis are distributed isotropically, and we integrate inward to $10m$ assuming component masses $m_1 = 0.55$ and $m_2 = 0.45$ and dimensionless spin parameters $\hat{a}_1 = \hat{a}_2 = 1$. The final spin angles show no alignment towards each other or towards the orbital axis, hence other mechanisms are needed to avoid ejecting merged black holes from their host galaxies.